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(54) Exercise apparatus

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(56) References cited:
WO-A-95/08369
FR-A- 2 709 067
US-A- 5 256 115

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Description

[0001] This invention relates to exercise apparatus according to the precharacterising part of claim 1. An exercise apparatus of this type is known from e.g. US-A-5 256 115.

[0002] The invention is particularly applicable to exercise apparatus designed to simulate the motion of a travelling body.

[0003] Exercise apparatus is known which allows the user to simulate an exercise in the form of a means of human powered transport or simply walking or running. Among these are treadmills, rowing machines and exercise cycles. They have been developed to allow the user to perform an exercise in a confined space that would otherwise require a large area. Other forms of exercise apparatus provide a force to exercise against. In this, they are static (producing a torque to exercise against) as opposed to dynamic (producing a motion).

[0004] One of the basic aspects of most types of apparatus of this kind is the simulation of the momentum of either the human body or the transport being simulated. This is commonly achieved by using a flywheel linked to the apparatus, counter to the inertia of which the user exerts a force in performing the exercise. As an example of this, the exercise treadmill provides a so-called 'rolling road' in the form of a conveyor belt powered by an electric motor. Typical motors are induction motors, brushed permanent magnet motors and brushless dc motors.

[0005] The 'runner' moves relative to the belt but actually remains substantially stationary. To take the weight of the runner, the flexible belt travels across a support such that the runner's leading foot hits the belt immediately above the support and is carried backwardly. The impact of the foot on the belt pinches the belt between the foot and the support creating a sudden load on the motor. The speed of the travelling belt is maintained by a flywheel operably mounted in relation to the motor so that little or no change in the speed of the belt is perceived by the runner as a result of the foot hitting the belt. Similarly, there are occasions in the running cycle when both feet are out of contact with the belt and it is equally important that the speed of the belt is not substantially increased before the next foot to land makes contact with the belt.

[0006] From this it will be appreciated that using a treadmill exercise apparatus involves the relatively sudden imposition and relief of loads on the motor as the feet perform the running action. Known drive systems which are cost-effective in such apparatus are unable to maintain the belt at a sufficiently constant speed. In order to reduce the speed fluctuation to an acceptable level, the flywheel is used to increase the inertia of the rotating components and damp out short-term fluctuations.

[0007] The mechanical dynamics of the system are dominated by the inertia of the flywheel and the friction in the belt/roller system. The system therefore has very slow and well-damped dynamics, and any electrical or mechanical disturbances will be substantially suppressed. Any device used for torque or speed control feedback may accordingly be of relatively low quality, in order to maintain overall costs.

[0008] It is well known that flywheels, by their nature, are relatively heavy items and often of a size which makes them awkward to integrate into a housing for the other, significantly smaller, components that will be associated with powering a piece of exercise apparatus. The presence of the flywheel in an exercise apparatus of the type described may significantly increase the size of the unit overall.

[0009] If the flywheel is removed from a prior art exercise machine in an effort to save cost and weight, the source of mechanical inertia is essentially removed. Thus, the control system will demand rapidly changing amounts of torque from the motor as the runner's foot lands on the moveable surface. The motor typically employed in such a machine has a relatively low bandwidth. It is therefore unable to react quickly enough to the change in torque demand and the speed of moveable surface accordingly varies to an unacceptable degree. Attempts to improve the response time by increasing the bandwidth of the controller tend to be counterproductive as the controller cost rises dramatically and the overall response time of the system is limited by the motor's bandwidth.

[0010] As a practical matter, the standard of flywheel that is cost effective to use in exercise apparatus may well be inadequately balanced. The motor typically runs at 5000rpm, which can mean that an inadequately balanced rotating flywheel gives rise to objectionable vibration while the apparatus is in use.

[0011] A further disadvantage of the use of a flywheel in exercise apparatus is that it can take a considerable time for the exercise machine to come to rest when the power is removed from the drive motor. This can have undesirable consequences in the event of the user stumbling and operating an emergency stop.

[0012] US-A-5256115, on which the preamble to claim 1 is based, discloses an electronic flywheel and clutch for pedal-type exercise apparatus. The exercise is performed against a load in the form of an electric motor. A speed reference command generator compares an input torque to a load torque setting to create a command signal which is applied to a servo for matching the input speed of the load to the command signal.

[0013] WO-A-95 08369 discloses an exercise resistance device. Exercise movement energy is dissipated by a motor and an electronic circuit. The effective inertia and drag of the device is user programmable.

[0014] FR-A-2709067 discloses apparatus for creating a resistant force in an exercise machine. The flux in an asynchronous motor is set by a variable drive signal to control the torque output resisting the exercise movement.

[0015] The present invention is characterised in that the electric machine is a switched reluctance machine; and in that state observer means are arranged to receive a signal indicative of at least one machine parameter to produce a machine disturbance compensation signal, and means are provided for applying the compensation signal to the controller signal to assist the convergence of the machine output with the demand input.

[0016] Particular embodiments of the invention are the subject of the dependent claims.

[0017] It has been realised that a switched reluctance motor has a relatively wide bandwidth. In effect, it acts as a 'torque source' - that is, the motor delivers the torque demanded from it within a time scale much less than the frequency of the fluctuations in the load. By coupling the switched reluctance motor with a wide bandwidth controller, for example, a system is provided that has a bandwidth wide enough to permit real-time control of the variation in motor speed output to within a suitably small amount without the need for flywheel. The state observer means makes the flywheel redundant. While state observer theory has been used in the past to control plant, it is not known to the inventors that it has been used to avoid the use of a component in a plant. Up to now, exercise apparatus has had to use a heavy mass to provide inertia. This is now obviated by the present invention. Removal of the flywheel reduces the weight of the apparatus and the tendency towards vibration that can be a consequence of an out of balance flywheel. The state observer technique of control has been used in the past to control systems. However, the inventors have recognised that the state observer technique can be used to replace the flywheel as opposed simply to controlling the existing system. The advantageous combination of the switched reluctance motor and the state observer control technique has given rise to exercise apparatus that is lighter and quicker to respond to changing demands.

[0018] Thus, when the runner's foot hits the belt of a treadmill, the small initial reduction in speed is detected and the control system reacts to bring the speed back to the demanded level.

[0019] In a dynamic exercise machine, such as a treadmill, the output of the machine is speed as this is linked directly to the speed the runner wishes to maintain. In a static machine, the output is torque or force against which the user exerts a torque or force. The machine parameters are rooted in rotor position as this is fundamental to operation of a switched reluctance machine. However, while the rotor position measured may be used to derive (e.g.) speed or another parameter, speed or torque could be measured directly. Another parameter that could be measured in order to derive a measure of the variable of concern is stator excitation current or, possibly, voltage developed. The control regimes for switched reluctance machines are well known to the person of ordinary skill in the art and will not be further described. The operation and control of switched reluctance motors is described in 'The Characteristics, Design and Applications of Switched Reluctance Motors and Drives' by Dr. J. M. Stephenson and Dr. R.J. Blake, PCIM'93, Nurnberg, Germany, June 1993 to which reference is hereby made.

[0020] Typically, the machine will comprise a rotor and a stator. The machine output is preferably selected from the group comprising machine rotor position, speed and torque.

[0021] Preferably, the at least one machine parameter is selected from the group comprising machine rotor position, speed, torque, current and voltage, the state observer means being responsive to the signal indicative of the at least one machine parameter.

[0022] In one particular form the apparatus further comprises means for producing a rotor position signal and means for producing a machine speed signal, the state observer means being arranged to produce the disturbance compensation signal in response to the rotor position signal and the machine speed signal. The motor speed signal may be derived from the rotor position signal.

[0023] The disturbance compensation signal may be produced from an estimate of the overall load change based on the signal indicative of the at least one machine parameter.

[0024] When the apparatus is a treadmill, the load on the machine includes a roller and the exercise means comprises a belt engaged by the roller, providing a rolling road surface on which to exercise by running. The exercise apparatus may also be constituted by a rowing machine or an exercise cycle.

[0025] A further advantage of the switched reluctance motor is that it is significantly cheaper than other motors which have correspondingly wide bandwidths.

[0026] The rotor position indication may be by means of a rotor position transducer or a binary encoder. Alternatively, a sensorless rotor position indicator may be used. The motor speed signal means may produce a motor speed signal by differentiating the signal produced by the rotor position indicator means with respect to time. Alternatively, a high bandwidth tachometer could be used.

[0027] The present invention can be put into practice in various ways, some of which will now be described by way of example with reference to the accompanying drawings in which :

Figure 1 is a schematic diagram of a treadmill according to the invention;

Figure 2 is a schematic diagram of a first embodiment of a controller for use in the treadmill of Figure 1;

Figure 3 is a graph of the control response characteristics of the controller in Figure 2 compared with those of a prior art controller;

Figure 4 is a flow diagram of an observer technique for second and third embodiments of a controller for use in

the treadmill of Figure 1;
Figure 5 is a graph of the variation in the required motor torque with time for a typical treadmill;
Figure 6 is a flow diagram showing an alternative observer technique for the second and third embodiments of the controller;
Figure 7 is a schematic diagram of the second embodiment of the controller which employs the observer of Figures 4 and 6 for use in the treadmill of Figure 1;
Figure 8 is a schematic diagram of the third embodiment of the controller which employs the observer of Figures 4 or 6 for use in the treadmill of Figure 1;
Figure 9 is a schematic diagram of the angle reference pattern used to generate an input to the controller of Figure 8;
Figures 10a to 10h are plots of the signals generated at the various stages in the controller of Figure 7, as a function of time;
Figures 11a to 11f are plots of the signals generated at the various stages in the controller of Figure 8, when arranged in a first manner, as a function of time;
Figures 12a and 12b are plots of the signals generated at the various stages in the controller of Figure 8, when arranged in a second manner, as a function of time;
Figures 13a to 13c are plots of the roller speed of the treadmill of Figure 1 as a function of time, when the belt is controlled by the controllers of Figs.7 and 8 respectively; and
Figures 14a and 14b are plots of angle against time for the rotor in the motor of Figure 1.

[0028] Referring to Figure 1 of the drawings, an exercise treadmill comprises a frame 10 to which a support rail 12 is attached. A running platform 14 having a low friction upper surface defining a substantially horizontal plane is supported by the frame. Front and rear rollers 16/18 in the form of elongate cylindrical members are attached to the frame at either end of the platform 14 by means of bearings such that the upper circumferential extent of each roller is generally aligned with the plane of the upper surface of the platform. A conveyor in the form of a flexible belt 20 is looped around the rollers 16/18 passing across the upper surface of the platform 14. Means for tensioning the belt, adjusting the inclination of the belt, etc., have been omitted for clarity.

[0029] The front roller 16 is a driven roller in this embodiment and the rear roller 18 is an idler. A first pulley wheel 22 is mounted to rotate with the drive roller 16. A switched reluctance motor 26 has a second pulley 24 which is drivingly engaged with the first pulley wheel 22 by a drive belt 28.

[0030] The belt 20 passing over the upper surface of the platform 14 and between the rollers 16/18 forms a rolling road supported by the platform 14. The rolling road moves across the upper surface of the platform 14 from the front to the rear, driven by the switched reluctance motor 26.

[0031] The motor is controlled by actuation of a switching circuit 30 in conventional manner in the field of switched reluctance motors. This is described in the paper 'The Characteristics, Design and Applications of Switched Reluctance Motors and Drives' by Stephenson and Blake, referred to above. The switch timing is effected by a controller 32 programmed to carry out a switching strategy that is designed to control the torque output of the motor with changes in the load.

[0032] At this point, a consideration of the control requirements is appropriate. In the case of a treadmill, the rolling road of the belt is run on by the user at the linear speed of movement of the belt so that the user is effectively at a standstill. The running speed can be varied by varying the speed of the belt. In the act of running, the user introduces each foot to the belt at a leading position. Without the presence of the platform 14, the belt would clearly have a spongey feel to it which would not be an accurate simulation of a satisfactory running surface. Therefore, the platform 14 supports the belt while each foot is in contact with it, but particularly as the lead foot hits the belt. At the moment of impact of the foot on the belt, the belt is pinched between the foot and the platform so that there is a sudden increase in the resistance to movement of the belt which must be countered by the motor. The overall load on the motor thus varies by the sudden application of the foot pinching the belt against the platform.

[0033] Figure 2 shows a controller for a treadmill, the controller having a high bandwidth which removes the need for a flywheel. The user-defined speed command is applied to a summing junction and then the error is applied to a low pass noise filter 310 and next to a switched reluctance controller 320 of the proportional-plus-integral (P+I) type. The torque demand signal which is the output of the controller 320 is used as the input to a conventional switched reluctance motor power converter 330 which includes a rectifier circuit for converting ac mains into a dc voltage. The dc voltage is switched across the phase windings of a switched reluctance motor with a typical output power of around 2kW. A rotor position encoder 340 is mounted in relation to the motor shaft to produce a feedback signal that is converted into a speed signal in a pulse-to-speed converter 350. This signal is in turn used as an input to the system to control the output of the motor according to the torque requirements. An encoder would typically have a position resolution one order of magnitude more accurate than a known rotor position transducer for a switched reluctance motor.

[0034] The actual speed of the roller 16 when controlled by the high bandwidth controller of the present invention described above is shown as a function of time by means of the continuous line in Figure 3. The output of a prior art controller which employs a flywheel is also shown, using the broken line in Figure 3. The maximum variation in the speed of the roller when controlled by the prior art controller is about 50 revolutions per minute (rpm) at a mean speed of 550 rpm. The maximum variation with the high bandwidth controller of Figure 2, however, is about 180 rpm for the same mean belt speed.

[0035] In the controller of Figure 2, the lack of a flywheel means that a high quality (low noise, low ripple) rotor position/speed sensor is desirable, typically an encoder which is substantially more expensive than the low quality RPT of the prior art controller with flywheel. However, small imperfections in the timing between sensor pulses and electrical noise are amplified twice in an RPT (and, to a lesser extent, an encoder). Firstly, they are amplified through converting rotor position to speed, which requires differentiation of the angle of the rotor with respect to time. Secondly, they are amplified through the high bandwidth controller itself. To put this in context, a 10% corruption on the position sensor signal in the controller of Figure 2 would render the fluctuations in the belt speed so substantial as to make a treadmill constructed with such a position sensor and no flywheel unusable.

[0036] An alternative approach to the control of the motor in the treadmill is illustrated in Figures 4-8. Here, the disturbance (i.e., the increased load on the motor generated when the foot impacts on the belt) is accommodated, and in a preferred embodiment substantially absorbed, using a controller which employs a composite state observer. The observer estimates the speed and/or load disturbance, and uses these estimates to control the system. The observable states and disturbances are estimated from any measurement and control inputs. The theory of the composite state observer is set out in 'Theory of Disturbance - accommodating Controllers' by C.D. Johnson, in Chapter 7 of the book 'Advances in Control and Dynamic Systems', Vol.12, edited by C.T. Leondes, Academic Press, 1976.

[0037] The basic principles of observer theory will now be explained with reference to Figures 4 to 6. It has been found, in practice, that the disturbance - that is, the variation in the torque required from the motor to maintain the belt at a substantially constant speed as the foot strikes the belt - has a distinguishable pattern or waveform structure similar to the one illustrated in Figure 5. It is this quasi-random combination of steps and ramps which allows the overall control of the system.

[0038] Generally, a waveform-structured disturbance $w(t)$ can be expressed as a semideterministic analytical equation of the form:

$$w(t) = W(f_1(t), f_2(t), \ldots, f_M(t); c_1, \ldots, c_L) \tag{1}$$

where $f_i(t)$, $i=1,2,\ldots M$, are known functions and c_K, $k=1,2,\ldots L$ are unknown parameters which may occasionally jump in value in a random manner.

[0039] The system of the present invention has been found to work well by using the limiting linear form of Equation (1) above:

$$w(t) = c_1 f_1(t) + c_2 f_2(t) + \ldots + c_M f_M(t) \tag{2}$$

[0040] That is, the disturbance can be expressed as some weighted linear combination of known basis functions $f_1(t)$, with unknown weighting coefficients c_i, which jump in value in a random manner from time to time.

[0041] In the case of disturbance to be dealt with in the present case, shown in Figure 5, the disturbance $w(t)$ may be expressed as:

$$w(t) = c_1 + c_2 t \tag{3}$$

with weighting coefficients c_1 and c_2 that change in value in a random manner. It will be understood, in view of these constraints on c_1 and c_2, that Equation 3 is therefore only semi-quantitative.

[0042] In order to design a controller based on this theory, it is next necessary to derive a state model - that is, a differential equation satisfied by Equation (2) almost everywhere. This is typically difficult as there are often many equally 'correct' differential equations which are satisfied by this general expression. Realistic control system disturbances of the type shown in Figure 5 are, however, usually Laplace transformable. It may then be shown that the disturbance $w(t)$ described by the general expression of Equation 2 satisfies the linear time-invariant homogenous differential equation:

$$\frac{d^{\rho} w}{dt^{\rho}} + q_{\rho}\frac{d^{\rho-1} w}{dt^{\rho-1}} + q_{\rho-1}\frac{d^{\rho-2} w}{dt^{\rho-2}} + \dots + q_2\frac{dw}{dt} + q_1 w = 0 \qquad (4)$$

where q_i $(i=1,2, \dots \rho)$ are known as they are independent of c_i and-depend only on the set of known functions $f_i(t)$.

[0043] In order to account mathematically for the fact the c_i may jump randomly, an external forcing function $w(t)$, which consists of a series of completely unknown, randomly arriving, random intensity impulsive functions, is added to Equation 4. This is preferably a Dirac delta function. Thus, finally:

$$\frac{d^{\rho} w}{dt^{\rho}} + q_{\rho}\frac{d^{\rho-1} w}{dt^{\rho-1}} + q_{\rho-1}\frac{d^{\rho-2} w}{dt^{\rho-2}} + \dots + q_2\frac{dw}{dt} + q_1 w = w(t) \qquad (5)$$

[0044] This single ρth order differential equation is more usefully written as a set of first order differential equations in the canonical form which will be familiar to those skilled in the art:

$$w = z_1 , \qquad (6)$$

$$\dot{z}_1 = z_2 + \sigma_1(t) ,$$

$$\dot{z}_2 = z_3 + \sigma_2(t) ,$$

$$\dot{z}_{\rho-1} = z_{\rho} + \sigma_{\rho-1}(t) ,$$

$$\dot{z}_{\rho} = -q_1 z_1 - q_2 z_2 - \dots - q_{\rho} z_{\rho} + \sigma_{\rho}(t) \qquad (7)$$

where the overdot indicates the first differential with respect to t and the Dirac delta function $w(t)$ of Equation 5 has been represented equivalently in Equations 6 and 7 in terms of a series of delta functions $\sigma_1(t)$ where $i=1,2,\dots,\rho$.

[0045] $z(t)$ is, generally, a ρ-dimensional vector describing the 'state' of the disturbance $w(t)$. It is analogous to the actual state x of a dynamical system where x is related to certain physical properties of the system. The value of the instantaneous state $z(t)$ of an uncertain disturbance $w(t)$ embodies all the information required to control a system even if future disturbances are unpredictable.

[0046] Turning now to the specific disturbance experienced in the system of the present invention and shown in Figure 5, it was shown in Equation 3 that $w(t)$ may be expressed in the form $w(t) = c_1$ *and* $c_2 t$, whence by inspection $w(t)$ satisfies the second order equation:

$$\frac{d^2 w}{dt^2} = w(t) \qquad (8)$$

where $w(t)$ is the unknown Dirac delta function. Rewriting this in the first order canonical form of Equations 6 and 7 gives:

$$w(t) = (1,0)\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} \qquad (9)$$

and

$$\dot{z}_1 = z_2 + \sigma_1(t),\ \dot{z}_2 = 0 + \sigma_2(t) \qquad (10)$$

[0047] The above theory forms the basis of a second embodiment of a controller for a treadmill or the like that is able to operate without a flywheel by absorbing the disturbances. The controller utilises the fact that the system control inputs $u(t)$ are linked to the current state $x(t)$ of the system and the current state $z(t)$ of the disturbance $w(t)$.

$$u(t) = \phi(x(t), z(t), t) \tag{11}$$

[0048] It is usually not possible to measure the states $x(t)$ and $z(t)$ directly. On the other hand, it is possible to measure the current system outputs $y(t)$ together with certain set points (or 'poles') in the system determining the rate, for example, at which the system returns to equilibrium during the absorption of a disturbance.

[0049] Provided the uncertain disturbances $w(t)$ have a waveform structure, and can be modelled by a linear state model of the form given in Equations 6 and 7, a so-called state observer can be employed to generate reliably accurate on-line, real-time estimates $\hat{x}(t)$ of the instantaneous system state. As will be described in connection with Figure 6, a composite state observer that also estimates on-line, real-time estimates of the instantaneous disturbance state $\hat{z}(t)$ may be constructed. In other words, the system control inputs $u(t)$, which are a function of $x(t)$, $z(t)$ and t, may be defined instead in terms of estimates:

$$u(t) = \phi(\hat{x}(t), \hat{z}(t), t) \tag{12}$$

[0050] The estimation errors $\varepsilon_x = x(t) - \hat{x}(t)$ *and* $\varepsilon_z = z(t) - \hat{z}(t)$ are forced to reach zero quickly with respect to the overall system settling times by setting the composite observer poles to values defined by the values of the matrices K_{xy}, where x and y are integers defining the matrix co-ordinates.

[0051] The basic observer technique will now be described in relation to Figure 4. The state equations of a disturbed system are taken to have the general form:

$$\dot{x} = A(t)x + B(t)u + F(t)w(t) \tag{13}$$

$$y = C(t)x + E(t)u(t) + G(t)w(t) \tag{14}$$

where u is the input (here, the total torque command), y is the online measured value of the actual system output, w (t) is a correction factor arising from unmeasured disturbances, errors in the model and parameter drifts, and x is the system state vector. The matrices A, B, C, E, F and G are assumed to be known.

[0052] In equation (13), $F(T)w(T)$ is usually considered to be a state 'driving' disturbance. In equation (14), $E(t)u(t)$ is a direct feedthrough, whereas $G(t)w(t)$ is usually considered to be a measurement disturbance.

[0053] The system state estimate $\hat{x}$ can be substituted into Equation 13 above:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + w(t) \tag{15}$$

[0054] Figure 4 shows schematically the state estimate equation of Equation 15, in the particular case where the error is derived from the difference between the measured system output value and the state estimate:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + K_{obs}(y - C\hat{x}) \tag{16}$$

K_{obs} is the settable system pole matrix (defining the observer gain) which is chosen to remove the error in the estimation within a timescale much shorter than the system settling time. $(y - C\hat{x})$ is an estimation error. This basic observer does not account for disturbances $w(t)$.

[0055] Estimates of both the system state $x(t)$ and the disturbance state $z(t)$ may be obtained from the composite state observer expression given in the following Equation:

$$\begin{pmatrix} \dot{\hat{x}} \\ \dot{\hat{z}} \end{pmatrix} = \left[\begin{array}{c|c} A + K_{11}C & FH + K_{11}GH \\ \hline K_{21}C & D + [K_{21}]GH \end{array} \right] \begin{pmatrix} \hat{x} \\ \hline \hat{z} \end{pmatrix} - \begin{pmatrix} K_{11} \\ \hline K_{21} \end{pmatrix} y + \begin{pmatrix} B \\ \hline 0 \end{pmatrix} u \qquad (17)$$

where A, B, C, E, F, and G are the (assumed known) matrices of Equations 13 and 14 above, and D and H are the matrix operators of Equations 9 and 10 - i.e. $w(t) = H(t)z$ *and* $\dot{z} = D(t)z + \sigma(t)$. As before, the values of K_{xy} are selected to cause the system to approach equilibrium rapidly.

[0056] A flow chart illustrating the composite state observer equation (Equation 17) is illustrated schematically in Figure 6.

[0057] Turning now to Figure 7, a block diagram of a motor controller for the treadmill of Figure 1 is shown. The controller incorporates the composite state observer of Figure 6 and a proportional-plus-integral (P+I) controller.

[0058] In Figure 7, a composite state observer 200 generates an estimate of the system state, x_2, which is the speed of the rotor of the switched reluctance motor 26 used to drive the belt 20 in Figure 1. The observer 200 also generates estimates of the load disturbance states, z_1 and z_2, caused by the runner's foot hitting the belt. The observer 200 has as inputs a signal from a rotor position transducer 210 and the control output u_{total} (i.e. the torque demand) of the system which sets the torque required by the motor 26.

[0059] The RPT 210 has an output which contains inherent random noise from mechanical edge jitter and so forth, as well as systematic errors arising from mechanical quantization error and mechanical edge error due to output beam width, placement problems, etc. For example, in an RPT having 8 teeth with 2 edges each and 3 sensor heads, there will be 48 edges per mechanical cycle and $2\pi/48 = \pi/24$ rads (7.5°) quantization error and approximately 4° mechanical edge error. In order to minimise spikes in the RPT signal, a grey-scale method for decoding the rotor position may be employed. Other techniques which will be familiar to those skilled in the art may of course be used. The actual angle of the rotor is shown in Figure 14a. The actual angle including the quantization and mechanical edge error from the RPT is shown in Figure 14b, and it is this which is input to the observer 200.

[0060] In the embodiment of Figure 7, only the speed estimate $_2$ is employed by the controller. This is subtracted at subtracter 220 from a speed reference x_2(ref) which is set by the user of the treadmill and is representative of the desired speed of the belt. Of course, the angle estimate $\hat{x}_1$ could be employed instead or as well, and the implementation will be apparent to one skilled in the art.

[0061] The output of the subtracter 220 is a signal indicative of the estimated speed error ε_s which is received by a proportional-plus-integral (P+I) speed tracking controller 230. The controller 230 generates a torque demand u_{track} which is the sum of the proportional error $K_p\varepsilon_2$ and the integrated error $K_i\int\varepsilon_2 dt$, K_p and K_i being multipliers. The P+I controller output u_{track} is a signal representative of the total torque that would be necessary to operate the motor at the required speed in the absence of any disturbances.

[0062] The load disturbance state estimates z_1 and z_2 produced by the observer 200 act as inputs to a disturbance absorbing controller (DAC) 260. The output of the DAC is a disturbance absorbing torque command w, which is a measure of the amount of torque adjustment necessary to cancel the effect of the load disturbance. Thus, the controller of Figure 7 generates a motor speed or torque compensation signal based on the values of u_{total} and the signal from the rotor position transducer 210. The disturbance absorbing torque command w and the tracking torque error u_{track} are summed at adder 250 to generate the total torque signal u_{total}.

[0063] The total torque signal u_{total} is finally filtered by the low pass filter 240 to improve the noise performance, i. e., to make the closed loop system robust to high frequency parasitic systems. The filtered output is fed to the controller 32 of Figure 1. As already mentioned, this filtered total torque signal U_{total} is additionally fed back to the observer 200.

[0064] Figure 7 is shown employing full state observer using the state estimate x_2. However, it will be appreciated that a reduced state observer could be employed. Indeed, by removing the observer entirely (shown by the dotted line between the disturbance observing controller 260 and the adder 250), a controller similar to that shown in Figure 2 is generated.

[0065] Figure 8 shows a further embodiment of a motor controller. Components common to the embodiments of both Figure 7 and Figure 8 are labelled similarly.

[0066] As with Figure 7, the composite state observer 200 has as inputs a signal from a rotor position transducer 210 and the output torque demand u_{total} of the system which sets the torque required by the motor 26 of Figure 1. In one form, the position and speed estimates x_1, x_2 are subtracted from their corresponding position and speed references x_1(ref), x_2(ref) at subtracter 220. The output of subtracter 200 is thus two signals ε_{x1}, ε_{x2}, which are combined by a (1x2) Gain matrix G_F to produce the tracking torque demand u_{track}. That is,

$$u_{track} = G_F \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} [\{x_1(ref) - \hat{x}_1\} + \{x_2(ref) - \hat{x}_2\}] \qquad (18)$$

where

$$\begin{bmatrix} K_1 \\ K_2 \end{bmatrix}$$

is the Gain matrix G_F. The tracking torque demand u_{track} is representative of the required torque in the absence of any disturbances. The tracking torque demand u_{track} is combined at adder 250 with the disturbance estimate $\hat{w}$ which is produced by a disturbance accommodating controller 260. The summed output u_{total} of the adder 250 is, as before, usually filtered by filter 240. The filtered output is indicative of the required torque from the motor 26.

[0067] As already described for Figure 7, the disturbance accommodating controller can be omitted entirely, at the expense of system performance. Such an arrangement is indicated by the broken line in Figure 8 between the disturbance accommodating controller 260 and the adder 250.

[0068] The angle and speed references x_1 and x_2 for the controller of Figure 8 are typically as shown in Figure 9. The angle reference x_1 increases linearly with time, and the slope of the angle reference with respect to time provides the angular velocity (speed) reference x_2. The angle reference is in the form of a sawtooth Modulo 2π so that the angle does not integrate to infinity.

[0069] Figure 9 also indicates the angle estimate $\hat{x}_1$ which will in practice follow the angle reference x_1 but with an error between the reference angle and the estimated angle.

[0070] Figures 10 to 13 show plots of the inputs and outputs of the control circuits of Figures 7 and 8.

[0071] Figures 10a to 10h show the signals generated at the various stages in the controller of Figure 7, as a function of time. All of the components shown in Figure 7 are connected (in particular, the disturbance accommodating controller 260 shown connected with a broken line).

[0072] In Figure 10a, the output of the RPT is shown. It should be noted that the output is of the form shown in Figure 14b, i.e., it includes the quantisation and other errors, even though these are not immediately visible in Figure 10a because of the different scale. Figs. 10b and 10c show the load disturbance state estimates $\hat{z}_1$ and $\hat{z}_2$ produced by the observer 200. Figure 10d shows the output $\hat{w}$ of the disturbance accommodating controller 260, which multiplies the disturbance estimates by a 1x2 vector which is in this case (-1,0). Figure 10e shows the estimated speed $\hat{x}_2$ generated by the composite state observer 200.

[0073] The speed error $\in_s$ which is an output of the subtracter 220 is shown in Figure 10f. The output u_{track} of the P+I speed tracking controller 230 is shown in Figure 10g, and the filtered sum of u_{track} and $\hat{w}$, u_{total}, is shown in Figure 10h.

[0074] Figures 11a to 11f show the signals generated at the various stages in the controller of Figure 8, as a function of time. In this case, the composite state observer generates both position and speed estimates $\hat{x}_1$ and $\hat{x}_2$. However, the disturbance accommodating controller 260 is not connected to the adder 250.

[0075] Figures 11a and 11b shown the angle and speed estimates $\hat{x}_1$ and $\hat{x}_2$. Figures 11c and lid show the position and speed error signals ε_{x1}, ε_{x2} which are combined by a (1x2) Gain matrix G_F to produce the tracking torque demand u_{track}. U_{track} is shown as a function of time in Figure 11e.

[0076] Figure 11f shows u_{total} once filtered. In this case, $u_{total} = u_{track}$ as the disturbance accommodating controller 260 is not connected.

[0077] Figures 12a to 12g show the signals generated at the various stages in the controller of Figure 8, with the various connections exactly the same as described above in relation to Figs. 11a to 11f except that the disturbance accommodating controller 260 is this time connected to the adder 250.

[0078] Figs. 12a to 12e correspond to Figs. 11a to 11e. Figure 12f shows $\hat{w}$ as a function of time. Finally, Figure 12g shows u_{total} once filtered. U_{total} is this time the sum of u_{track} and $\hat{w}$.

[0079] A typical plot of the roller speed of the treadmill of Figure 1 as a function of time, when the belt is controlled by the controller of Figure 7, and with the connections as described with reference to Figs. 10a-10h is shown in Figure 13a.

[0080] A similar plot of the belt speed of the treadmill of Figure 1 as a function of time, this time with the belt controlled by the controller of Figure 8 and with the connections is described with reference to Figs. lla-llf, is shown in Figure 13b.

[0081] Figure 13c shows the speed of the belt in Figure 1 when controlled by the controller of Figure 8 but with the connections as described with reference to Figures 12a-12g.

[0082] All plots are based on 2kW motor, rotating at a nominal 500rpm, with a standard RPT. The composite state observer poles are set at -80, -100, -110 and -120. These values have been chosen to force the error in the estimates to tend to zero at a suitably rapid rate for a 2kW motor.

[0083] The controllers described in connection with Figures 2, 7 and 8 are merely exemplary. The skilled reader will appreciate that other controllers which employ state observation could be used to control the motor, and indeed techniques other than the P+I solution described in connection with Figure 2 are envisaged.

[0084] Clearly, the response of the controller will depend upon the number of components employed (i.e. the complexity of the observer). Nonetheless, the speed at which the system settles following a disturbance also depends upon the gain of the closed loop defining the control system. This is in turn governed largely by the quality of the output from the RPT. Of course, improving the quality of the RPT, or indeed replacing it with an encoder, introduces additional cost. It has been found in practice that, when the poles of the control loop are set as above, it is possible to employ a standard RPT whilst, as shown in Figure 11, the system still typically settles within 30 ms. This is short enough that the user tends not to notice the variation in the belt speed. The overall belt speed control compares favourably with that of the prior art system including a flywheel, but with a reduction in cost, size and weight.

[0085] It will be appreciated that this invention is applicable to other exercise apparatus in which the prior art flywheel has been used to maintain the motor speed substantially constant in the presence of sudden changes in load. For example, rowing machines, where the flywheel simulates the inertia of the oars and/or the boat and/or the water displaced by the oars, and exercise cycles, where the flywheel simulates the inertia of the user and a bicycle.

[0086] Further, although the invention has been described in connection with a switched reluctance motor, other motors such as a brushless d.c. permanent magnet motor could be used. The switched reluctance motor has the advantages of relative cheapness and a very high torque to inertia ratio, which is particularly useful in the second embodiment of the present invention as it allows the control system designer to consider the motor as a torque source. Also, rotor position measurement is more easily achieved at low speeds in a switched reluctance motor than in a permanent magnet a.c. motor, provided sensorless rotor position detection is employed.

[0087] Accordingly, the principles of the invention, which have been disclosed by way of the above examples and discussion, can be implemented using various rotor arrangements. Those skilled in the art will readily recognise that these and various other modifications and changes can be made to the present invention without strictly following the exemplary applications illustrated and described herein and without departing from the scope of the present invention which is set forth in the following claims.

Claims

1. Exercise apparatus comprising: an electric machine (26); a load (16) operably connected with the machine; user exercise means (20) arranged to vary the overall load on the machine when in use; and a controller (32) for controlling an output of the machine, the controller including means for receiving a demand input, and means (320) for producing a control signal (u) for adjusting the machine output in accordance with the demand input, **characterised in that** the electric machine is a switched reluctance machine; and **in that** state observer means (200) are arranged to receive a signal indicative of at least one machine parameter to produce a machine disturbance compensation signal ($\hat{z}$); and means (250) are provided for applying the compensation signal to the controller signal to assist the convergence of the machine output with the demand input.

2. Apparatus as claimed in claim 1 in which the machine comprises a rotor and a stator and the machine output is selected from the group comprising: machine rotor position; speed; and torque.

3. Apparatus as claimed in claim 1 or 2, including means for producing the signal indicative of at least one machine parameter, the at least one machine parameter being selected from the group comprising: machine rotor position; speed; torque; current and voltage.

4. Apparatus as claimed in claim 1 in which the machine comprises a rotor and a stator and the machine parameters include rotor position and machine speed, the apparatus further including means (210) for producing a rotor position signal and means for producing a machine speed signal (x), the state observer means being arranged to produce the disturbance compensation signal in response to the rotor position signal and the machine speed signal.

5. Apparatus as claimed in claim 4 in which the motor speed signal means are arranged -to produce the signal indicative of motor speed from the rotor position signal.

6. Apparatus as claimed in claim 4 in which the state observer estimates the speed and position of the rotor in de-

pendence upon the control signal and the rotor position signal.

7. Apparatus as claimed in claim 6 in which the compensation signal is produced from an estimate (z) of the load change on the user exercise means.

8. Exercise apparatus as claimed in claim 7 in which the rotor position and machine speed estimates and the load change estimate are related to the speed control signal and the rotor position input by the equation:

$$\begin{pmatrix} \dot{\hat{x}} \\ \hline \dot{\hat{z}} \end{pmatrix} = \left[\begin{array}{c|c} A+K_{11}C & FH+K_{11}GH \\ \hline K_{21}C & D+[K_{21}]GH \end{array}\right] \begin{pmatrix} \hat{x} \\ \hline \hat{z} \end{pmatrix} - \begin{pmatrix} K_{11} \\ \hline K_{21} \end{pmatrix} y + \begin{pmatrix} B \\ \hline 0 \end{pmatrix} u$$

where A, B, C, D, E, F, G, H, K_{11} and K_{21} are known matrices and/or vectors associates with the apparatus, u is the speed control signal, y in the rotor position input from the rotor position indicator means, $\hat{x}_1$ is the rotor position estimate, $\hat{x}_2$ is the rotor speed estimate, and $\hat{z}_1$ and $\hat{z}_2$ are the load change estimates.

9. Exercise apparatus as claimed in any of the preceding claims, in which the exercise apparatus is a treadmill, the load including a roller (16) and the exercise means comprising a conveyor (20) engaged by the roller providing a rolling road surface.

10. Apparatus as claimed in any of claims 1 to 7 in which the exercise apparatus is a rowing machine or an exercise cycle.

11. Apparatus as claimed in claim 1, including a comparator (220) for comparing a speed estimate output ($\hat{x}_2$) from the state observer means with a speed reference signal (x_2), as the demand input, to produce an error signal (ε_s); and an adder (250) for adding the compensation signal (w) to the error signal to assist in the convergence of the machine output with the demand input.

Patentansprüche

1. Übungsgerät, welches umfasst: eine elektrische Maschine (26); eine Last (16), die funktionell mit der Maschine verbunden ist; eine Übungseinrichtung (20) für einen Benutzer, die so gestaltet ist, dass die Gesamtlast an der Maschine während der Benutzung verändert werden kann; und eine Steuerung (32) zum Steuern eines Ausganges der Maschine, wobei die Steuerung Mittel zum Empfang einer angeforderten Eingabe und Mittel (320) zur Erzeugung eines Steuersignals (u) zur Anpassung des Maschinenausganges an die angeforderte Eingabe besitzt, **dadurch gekennzeichnet, dass** die elektrische Maschine eine geschaltete Reluktanzmaschine ist; und dadurch, dass eine Zustandsüberwachungseinrichtung (200) angeordnet ist, um ein Signal zu empfangen, welches zumindest für einen Maschinenparameter aussagefähig ist, um ein Maschinenstörungs-Kompensationssignal ($\hat{z}$) zu erzeugen, und Einrichtungen (250) vorgesehen sind, um das Kompensationssignal mit dem Steuersignal zu verwenden, um die Annäherung des Maschinenausganges an die angeforderte Eingabe zu unterstützen.

2. Übungsgerät nach Anspruch 1, in welchem die Maschine einen Rotor und einen Stator umfasst und der Maschinenausgang aus einer Gruppe ausgewählt wird, welche umfasst: die Rotorposition der Maschine, die Geschwindigkeit und das Drehmoment.

3. Übungsgerät nach Anspruch 1 oder 2, welches eine Einrichtung zur Erzeugung des Signals umfasst, welches fiir mindestens einen Maschinenparameter aussagefähig ist, wobei der mindestens eine Maschinenparameter aus einer Gruppe ausgewählt ist, welche umfasst: die Rotorposition der Maschine, die Geschwindigkeit; das Drehmoment; Strom und Spannung.

4. Übungsgerät nach Anspruch 1, bei welchem die Maschine einen Rotor und einen Stator umfasst und die Maschinenparameter die Rotorposition und die Geschwindigkeit der Maschine umfassen, und das Gerät weiterhin Einrichtungen (210) zur Erzeugung eines Rotorpositionssignals und Einrichtungen zur Erzeugung eines Maschinen-

geschwindigkeitssignals (x) umfasst, wobei die Zustandsüberwachungseinrichtung vorgesehen ist, um das Störungskompensationssignal in Abhängigkeit vom Rotorpositionssignal und dem Maschinengeschwindigkeitssignal zu erzeugen.

5. Übungsgerät nach Anspruch 4, in welchem die Maschinengeschwindigkeitssignaleinrichtungen vorgesehen sind, um das für die Maschinengeschwindigkeit maßgebende Signal aus dem Rotorpositionssignal zu erzeugen.

6. Übungsgerät nach Anspruch 4, in welchem die Zustandsüberwachung die Geschwindigkeit und die Rotorposition anhand des Steuersignals und des Rotorpositionssignals einschätzt.

7. Übungsgerät nach Anspruch 6, in welchem das Kompensationssignal aus einer Einschätzung (z) der Belastungsänderung auf der Übungseinrichtung für den Benutzer erzeugt wird.

8. Übungsgerät nach Anspruch 7, in welchem die Rotorposition und die eingeschätzte Maschinengeschwindigkeit sowie die eingeschätzte Belastungsänderung zu dem Geschwindigkeitssteuersignal und dem Rotorpositionseingang durch die Gleichung in Beziehung gesetzt werden:

$$\begin{pmatrix} \dot{\hat{x}} \\ \hline \dot{\hat{z}} \end{pmatrix} = \left[\begin{array}{c|c} A+K_{11}C & FH+K_{11}GH \\ \hline K_{21}C & D+[K_{21}]GH \end{array}\right] \begin{pmatrix} \hat{x} \\ \hline \hat{z} \end{pmatrix} - \begin{pmatrix} K_{11} \\ \hline K_{21} \end{pmatrix} y + \begin{pmatrix} B \\ \hline 0 \end{pmatrix} u$$

wobei A, B, C, D, E, F, G, H, K_{11} und K_{21} bekannte, mit dem Gerät in Verbindung stehende Matrizen und /oder Vektoren sind, und u das Geschwindigkeitssteuersignal, y die von der Rotorpositionsanzeigeeinrichtung eingegebene Rotorposition, x_1 die eingeschätzte Rotorposition, x_2 die eingeschätzte Rotorgeschwindigkeit, und z_1 sowie z_2 die eingeschätzten Belastungsänderungen darstellen.

9. Übungsgerät nach einem der vorhergehenden Ansprüche, bei welchem das Übungsgerät eine Laufeinrichtung ist, wobei die Last eine Rolle (16) umfasst und die Übungseinrichtung einen Förderer (20) besitzt, der mit der Rolle zusammenwirkt und eine rollende Lauffläche darstellt.

10. Übungsgerät nach einem der Ansprüche 1 bis 7, bei welchem das Übungsgerät eine Rudereinrichtung oder ein Übungsfahrrad ist.

11. Übungsgerät nach Anspruch 1, welches einen Komparator (220) enthält, um einen eingeschätzten Geschwindigkeitsausgang (x_2) von der Zustandsüberwachungseinrichtung mit einem Geschwindigkeitsreferenzsignal (x_2) als angeforderte Eingabe zu vergleichen, um eine Fehlersignal (ε_s) zu erzeugen; sowie einen Summierer (250) zum Summieren des Kompensationssignals (w) mit dem Fehlersignal, um die Annäherung des Maschinenausganges an die angeforderte Eingabe zu unterstützen..

Revendications

1. Appareil d'exercice comprenant: une machine électrique (26); une charge (16) reliée de façon opérationnelle à la machine; un moyen d'exercice de l'utilisateur (20) disposé de manière à faire varier la charge totale sur la machine lors de son utilisation; et un régulateur (32) permettant de réguler une sortie de la machine, le régulateur comprenant des moyens de réception d'une entrée d'une demande, et des moyens (320) de production d'un signal de commande (u) permettant de régler la sortie de la machine en fonction de l'entrée de la demande, **caractérisé en ce que** la machine électrique est une machine à réluctance commutée; et **en ce que** des moyens observateurs d'état (200) sont disposés de manière à recevoir un signal indicatif d'au moins un paramètre de la machine afin de produire un signal de compensation de perturbation de la machine (z); et des moyens (250) sont prévus pour appliquer le signal de compensation au signal du régulateur afin de contribuer à la convergence de la sortie de la machine avec l'entrée de la demande.

2. Appareil suivant la revendication 1, dans lequel la machine comprend un rotor et un stator, et la sortie de la machine

est sélectionnée à partir du groupe formé de: la position du rotor de la machine, la vitesse et le couple.

3. Appareil suivant la revendication 1 ou 2, comprenant des moyens de production du signal indicatif d'au moins un paramètre de la machine, ledit au moins un paramètre de la machine étant sélectionné à partir du groupe formé de: la position du rotor de la machine, la vitesse, le couple, le courant et la tension.

4. Appareil suivant la revendication 1, dans lequel la machine comprend un rotor et un stator, et les paramètres de la machine comprennent la position du rotor et la vitesse de la machine, l'appareil comprenant en outre un moyen (210) de production d'un signal de position du rotor et un moyen de production d'un signal de vitesse de machine (x), les moyens observateurs d'état étant disposés de manière à produire le signal de compensation de perturbation en réponse au signal de position du rotor et au signal de vitesse de la machine.

5. Appareil suivant la revendication 4, dans lequel les moyens de signal de vitesse du moteur sont disposés de manière à produire le signal indicatif de la vitesse du moteur à partir du signal de position du rotor.

6. Appareil suivant la revendication 4, dans lequel l'observateur d'état estime la vitesse et la position du rotor en fonction du signal de commande et du signal de position du rotor.

7. Appareil suivant la revendication 6, dans lequel le signal de compensation est produit à partir d'une estimation (z) du changement de charge sur le moyen d'exercice de l'utilisateur.

8. Appareil d'exercice suivant la revendication 7, dans lequel l'estimation de la position du rotor et de la vitesse de la machine et l'estimation du changement de charge sont reliés au signal de régulation de la vitesse et à l'entrée de la position du rotor selon l'équation:

$$\begin{pmatrix} \dot{\hat{x}} \\ \hline \dot{\hat{z}} \end{pmatrix} = \left[\begin{array}{c|c} A + K_{11}C & FH + K_{11}GH \\ \hline K_{21}C & D + [K_{21}]GH \end{array} \right] \begin{pmatrix} \hat{x} \\ \hline \hat{z} \end{pmatrix} - \begin{pmatrix} K_{11} \\ \hline K_{21} \end{pmatrix} y + \begin{pmatrix} B \\ \hline 0 \end{pmatrix} u$$

où A, B, C, D, E, F, G, H, K_{11} et K_{21} sont des matrices connues et/ou des vecteurs associés à l'appareil, u est le signal de régulation de la vitesse, y est l'entrée de la position du rotor provenant du moyen indicateur de position du rotor, $\hat{x}_1$ est l'estimation de la position du rotor, $\hat{x}_2$ est l'estimation de la vitesse du rotor, et $\hat{z}_1$ et $\hat{z}_2$ sont les estimations du changement de charge.

9. Appareil d'exercice suivant l'une quelconque des revendications précédentes, dans lequel l'appareil d'exercice est un tapis roulant, la charge comprenant une rouleau (16) et le moyen d'exercice comprenant un convoyeur (20) engagé par le rouleau et fournissant une surface routière roulante.

10. Appareil suivant l'une quelconque des revendications 1 à 7, dans lequel l'appareil d'exercice est un rameur ou un vélo d'exercice.

11. Appareil suivant la revendication 1, comprenant un comparateur (220) permettant de comparer une sortie estimée de vitesse ($\hat{x}_2$) provenant des moyens observateurs d'état avec un signal de référence de vitesse (x_2), comme entrée de la demande, pour produire un signal d'erreur (ε_s); et un additionneur (250) pour ajouter le signal de compensation (w) au signal d'erreur afin d'aider à la convergence de la sortie de la machine avec l'entrée de la demande.

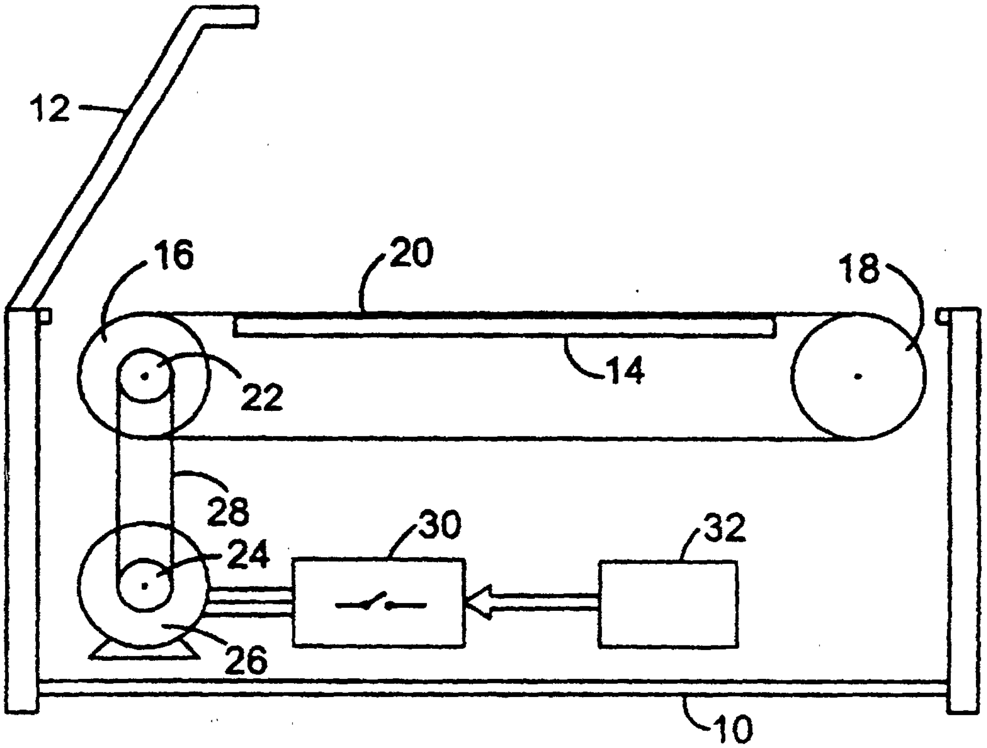
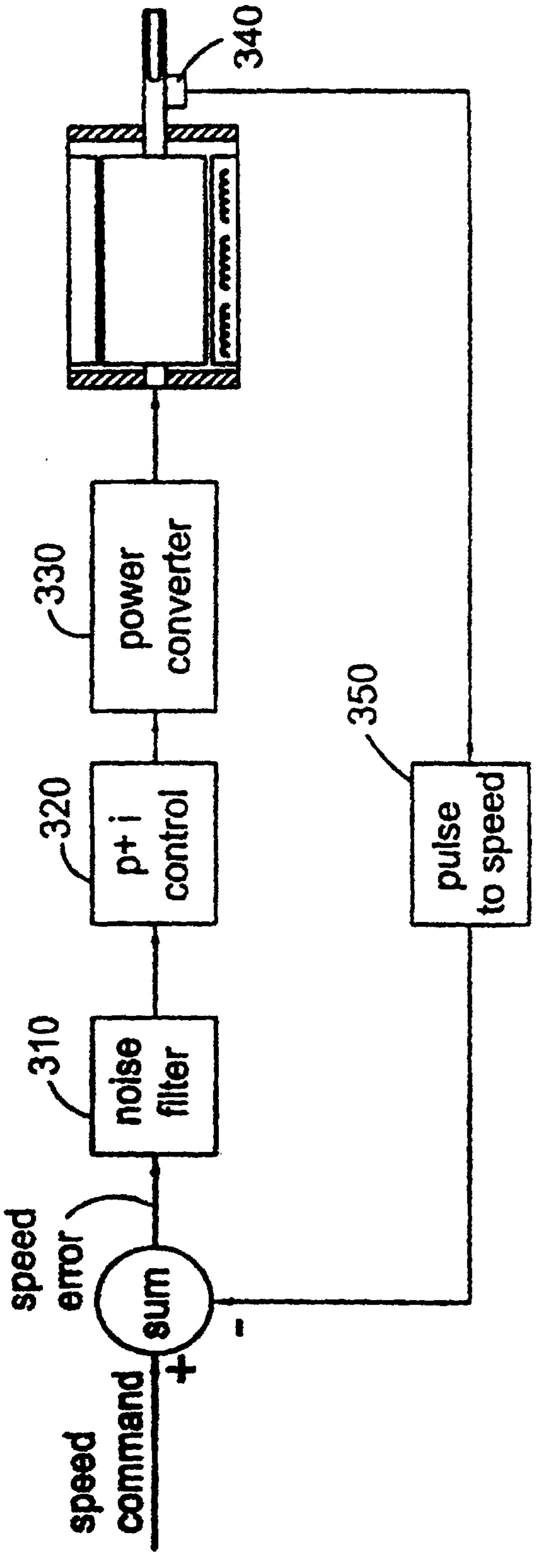


Fig 1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+
-
sum
speed error
310
noise filter
320
p+ i control
330
power converter
340
350
pulse to speed

Fig 2

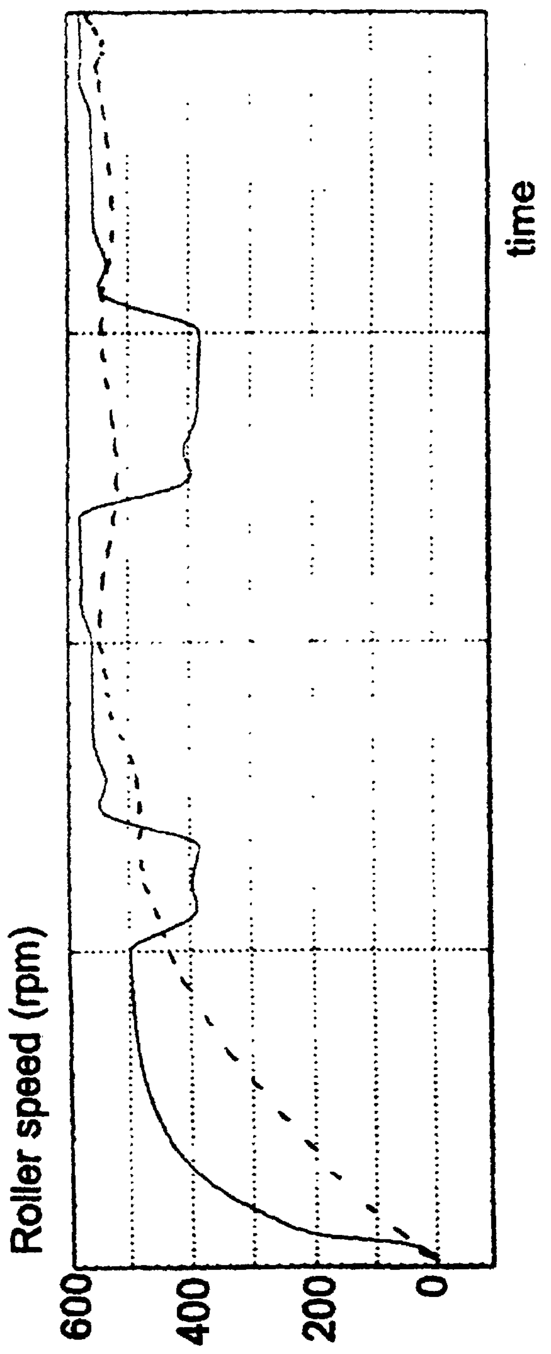

Fig 3

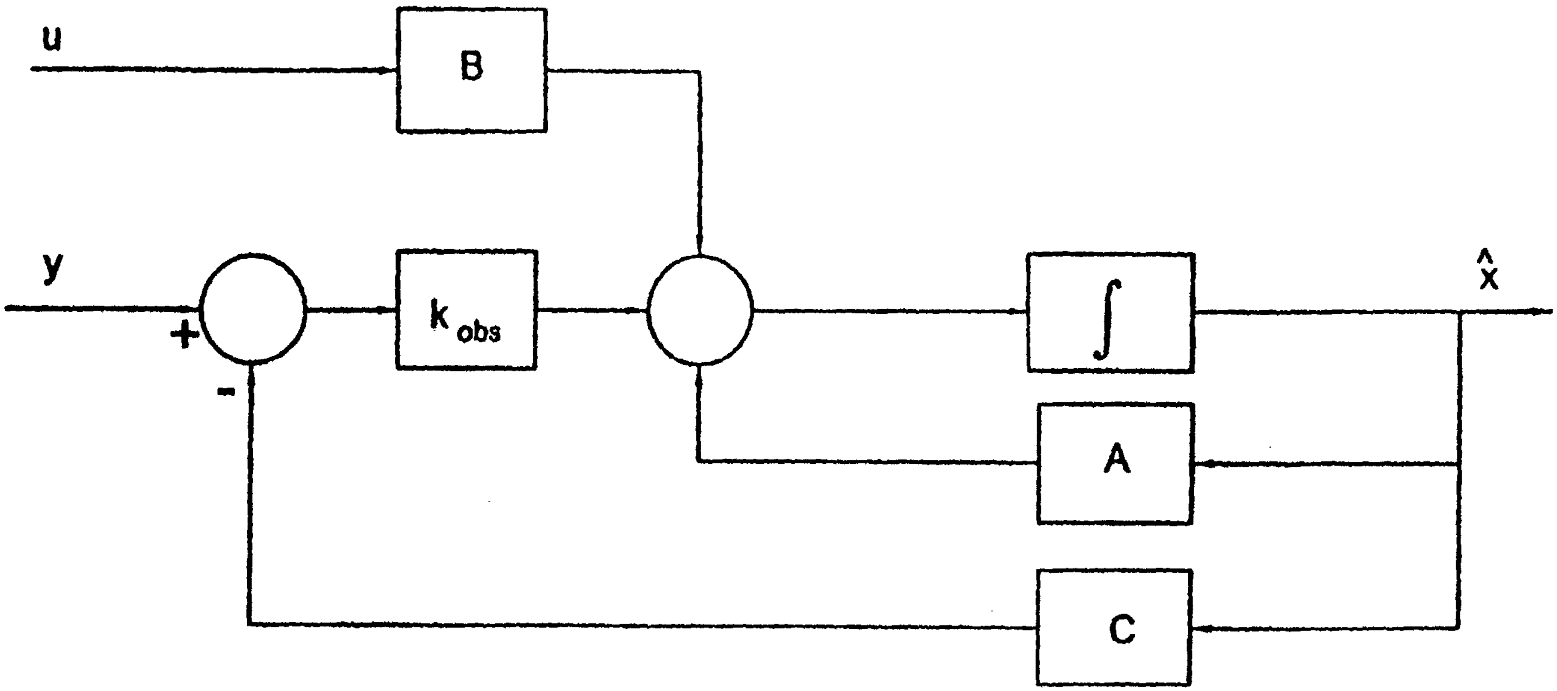

Fig 4

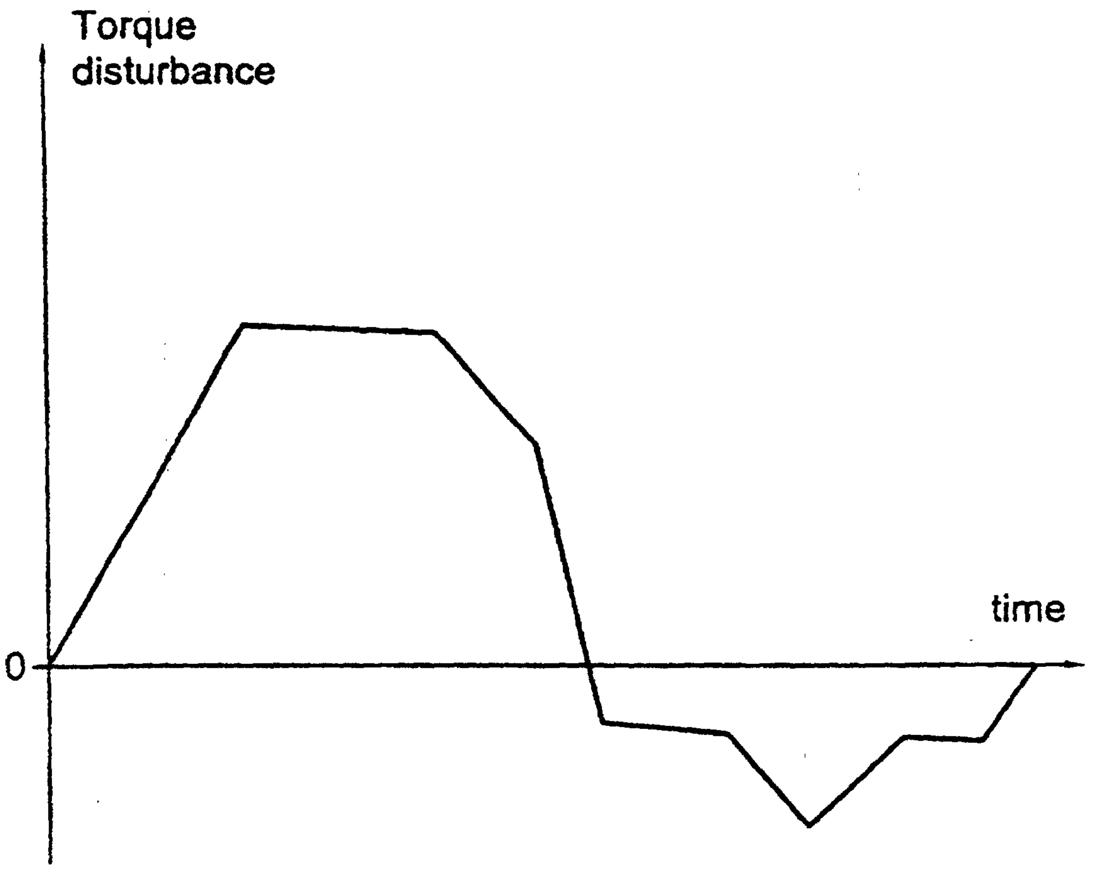

Fig 5

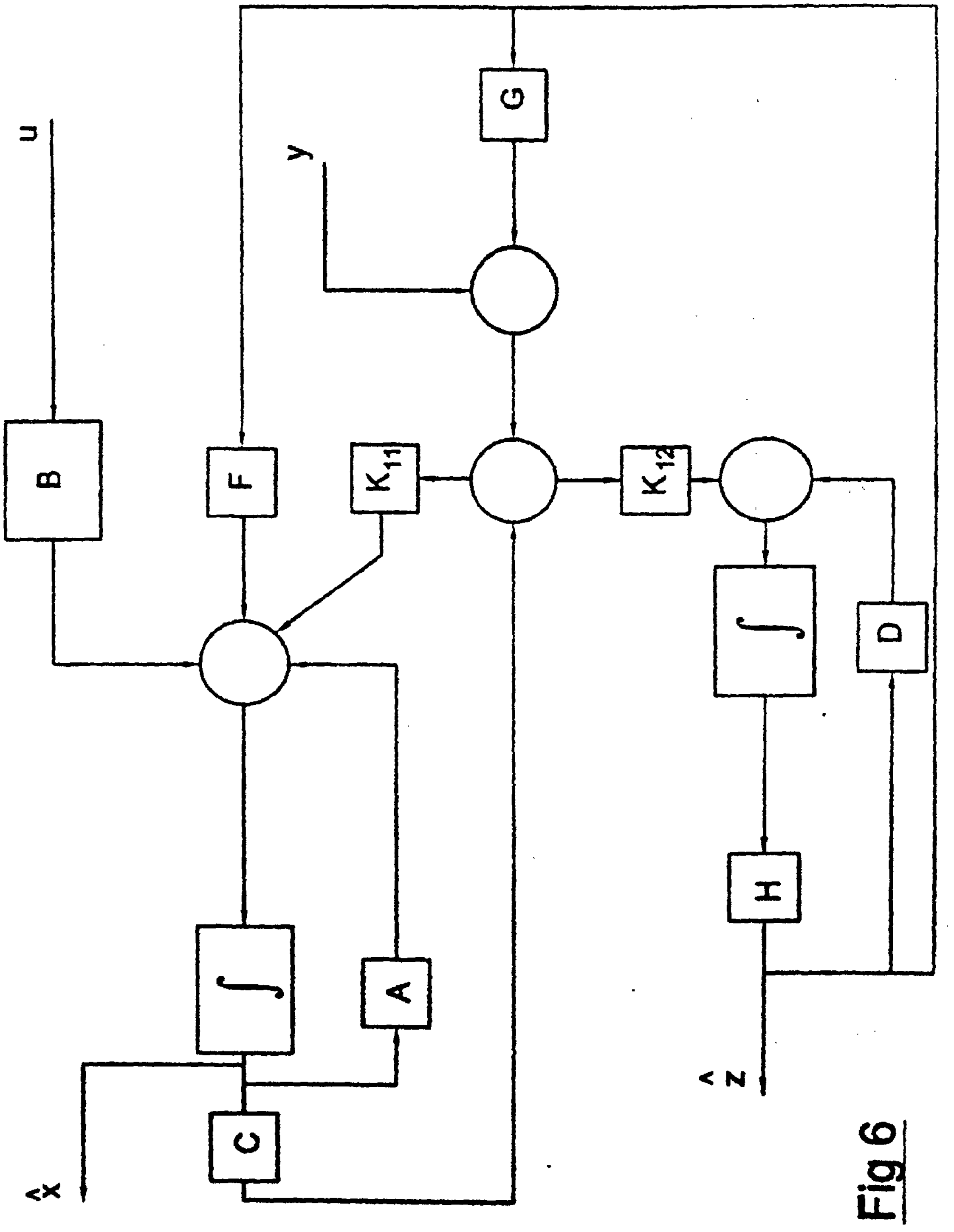

Fig 6

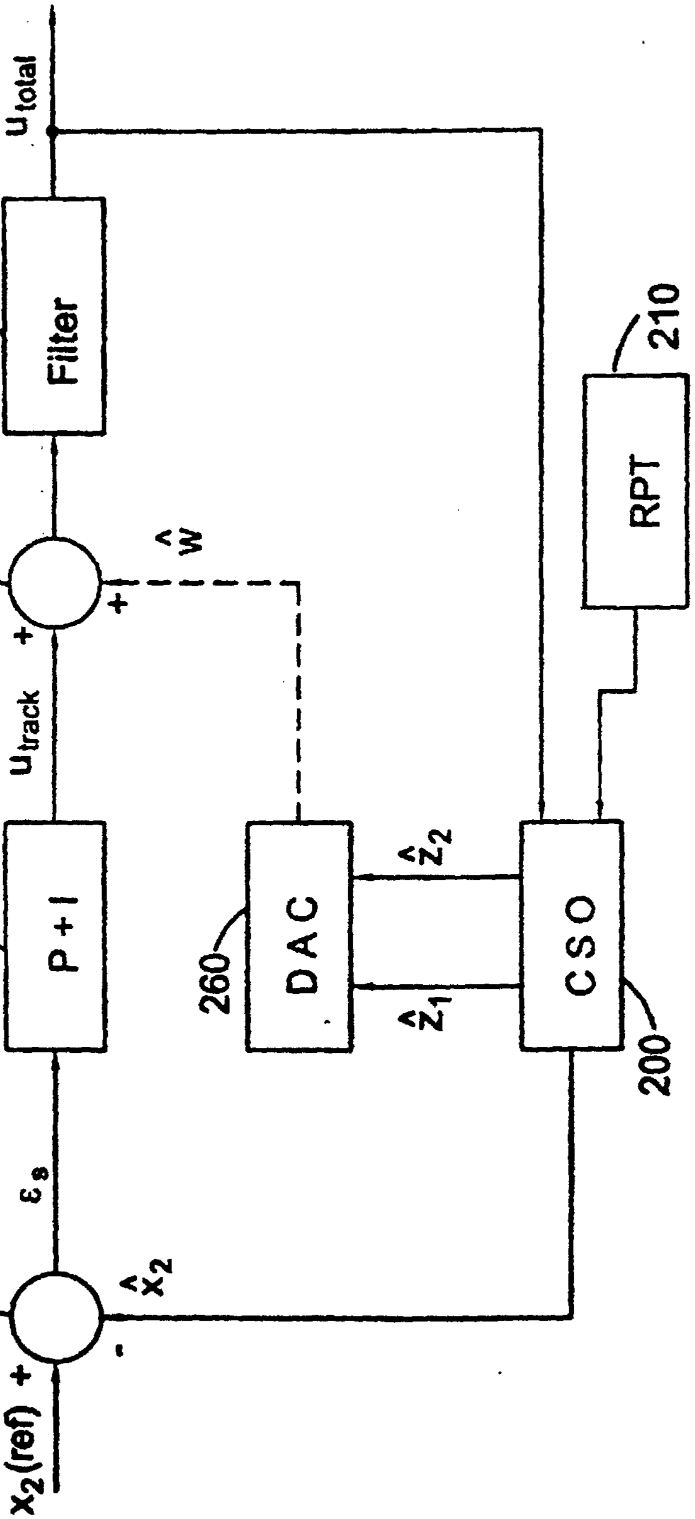
x_2(ref)
+
-
220
ε_s
$\hat{x}_2$
230
P + I
u_{track}
+
+
250
$\hat{w}$
240
Filter
u_{total}
260
DAC
$\hat{z}_1$
$\hat{z}_2$
CSO
200
RPT
210

Fig 7

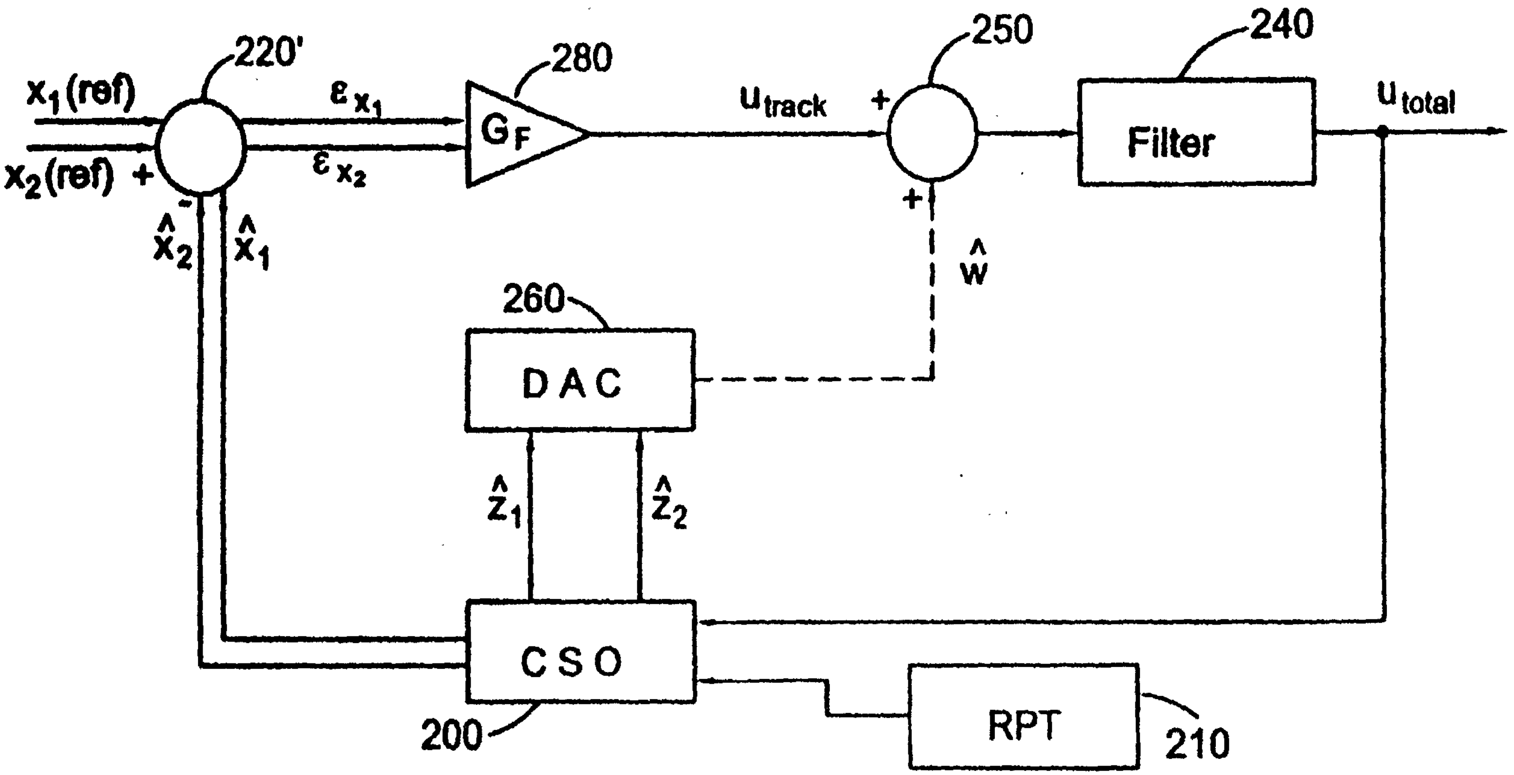
x_1(ref)
x_2(ref)
+
-
220'
ε_{x_1}
ε_{x_2}
$\hat{x}_2$
$\hat{x}_1$
280
G_F
u_{track}
+
250
+
$\hat{w}$
240
Filter
u_{total}
260
DAC
$\hat{z}_1$
$\hat{z}_2$
CSO
200
RPT
210

Fig 8

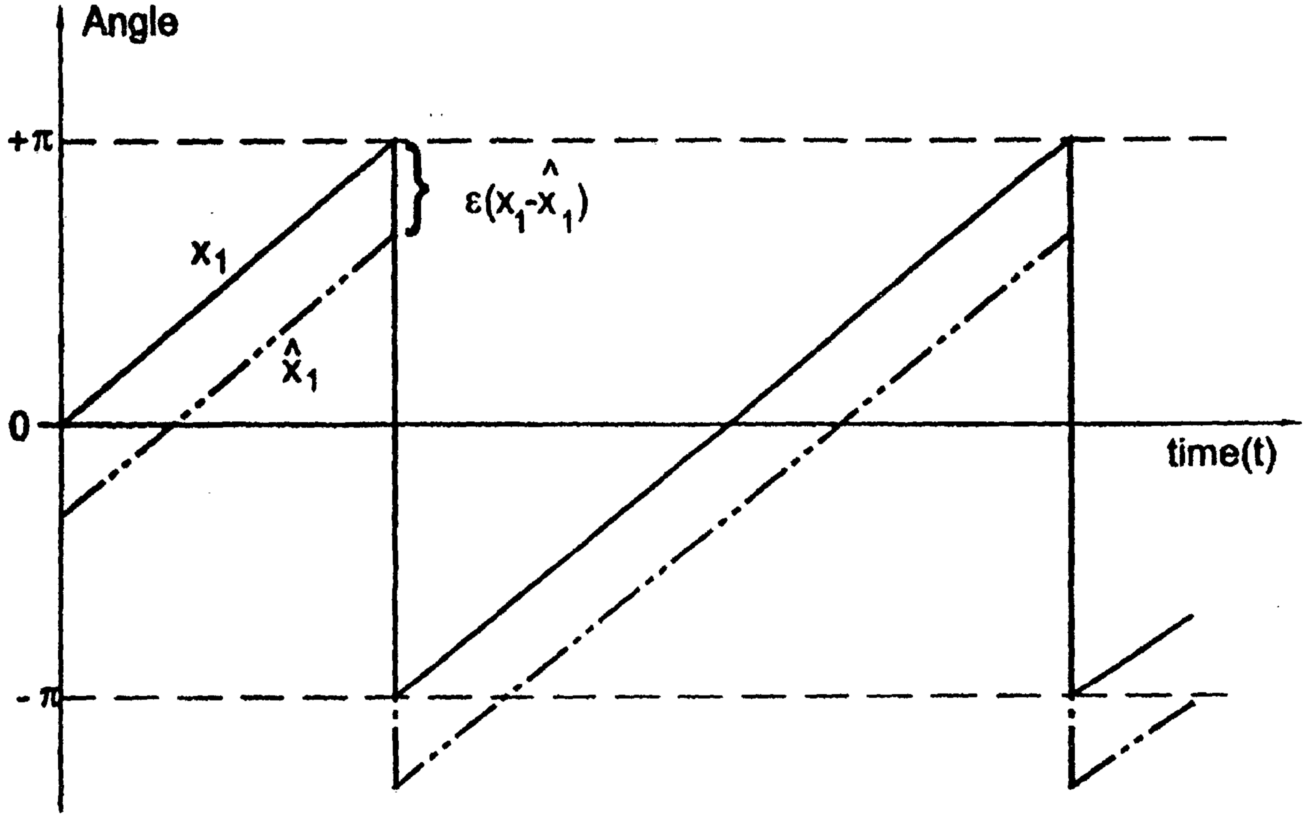

Fig 9

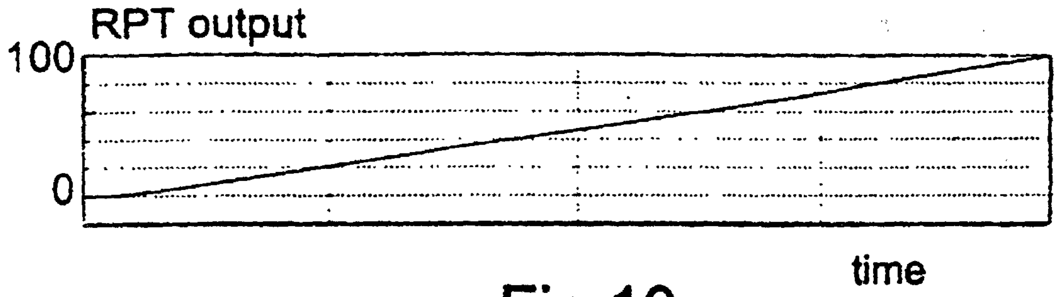

Fig 10a

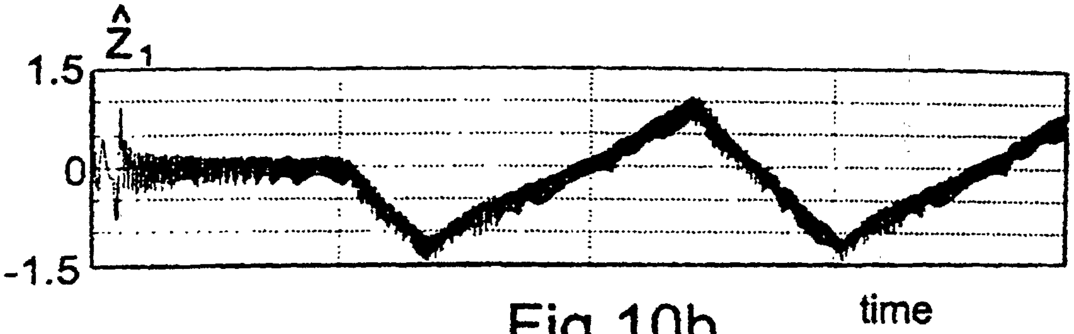

Fig 10b

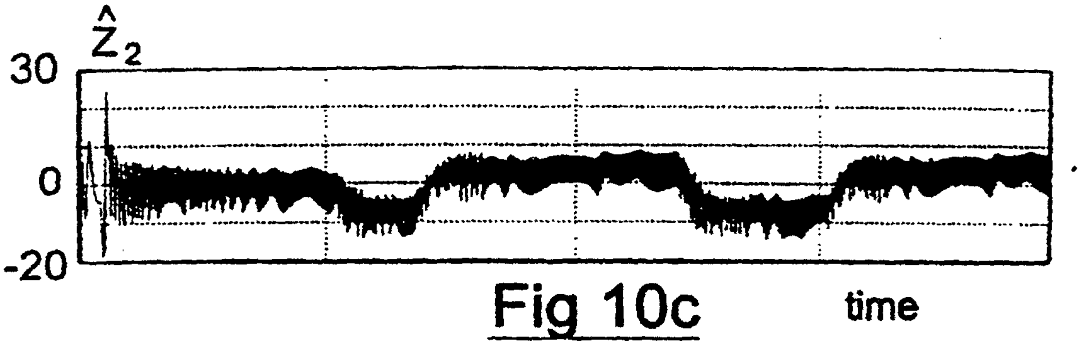

Fig 10c

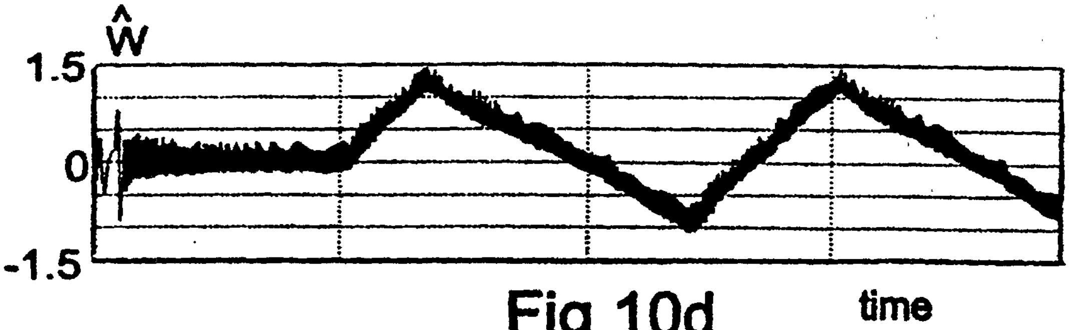

Fig 10d

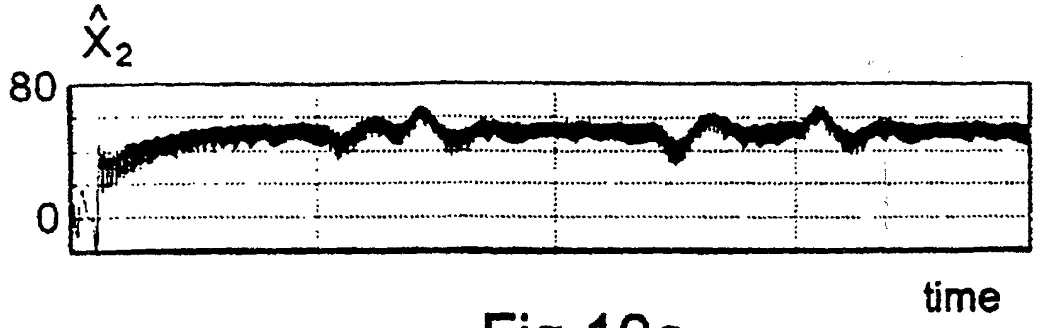

Fig 10e

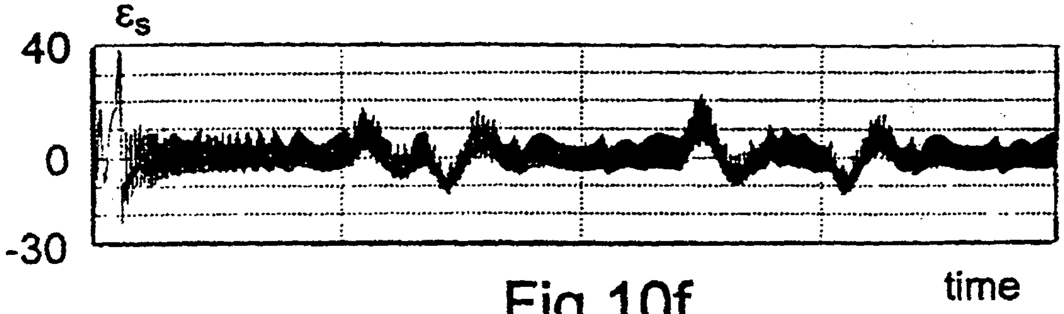

Fig 10f

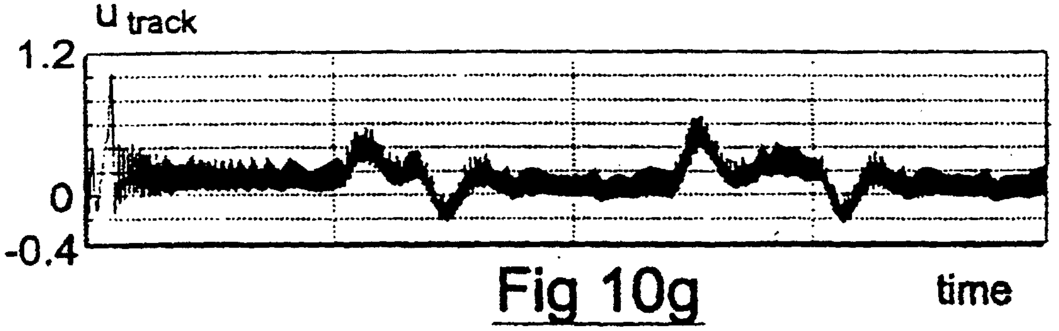

Fig 10g

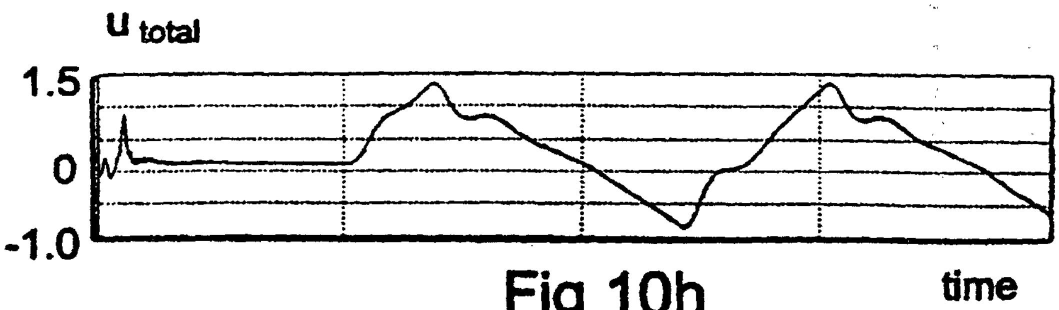

Fig 10h

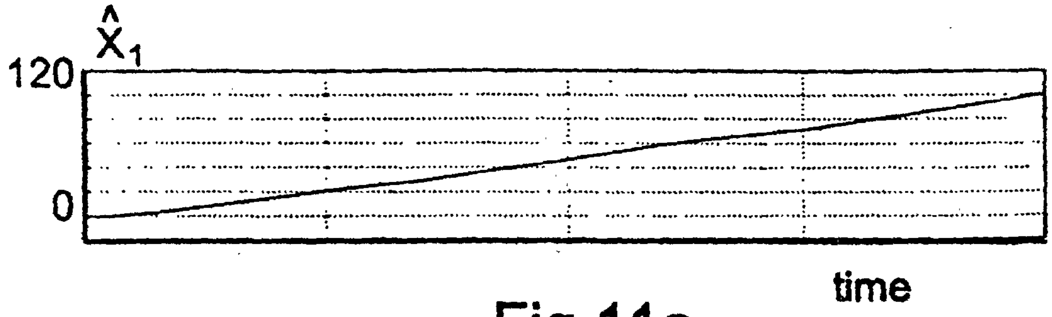

Fig 11a

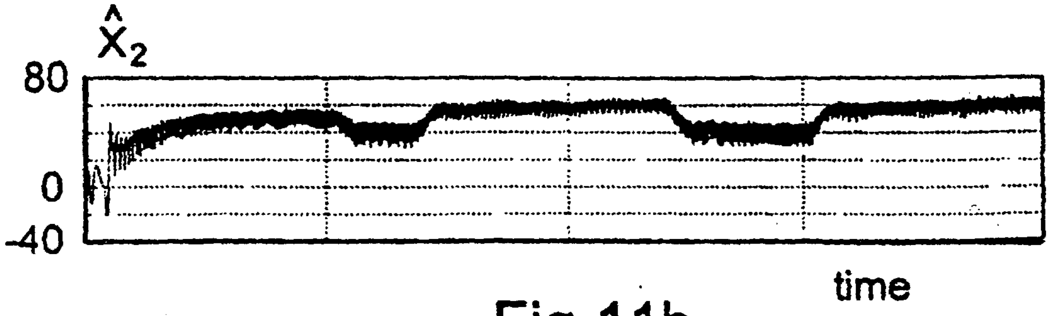

Fig 11b

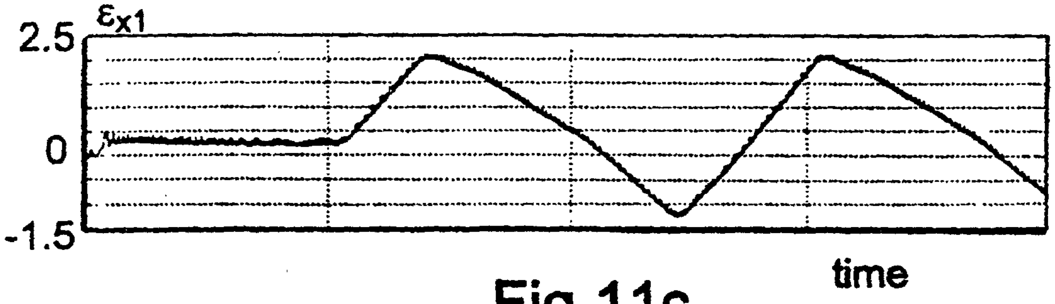

Fig 11c

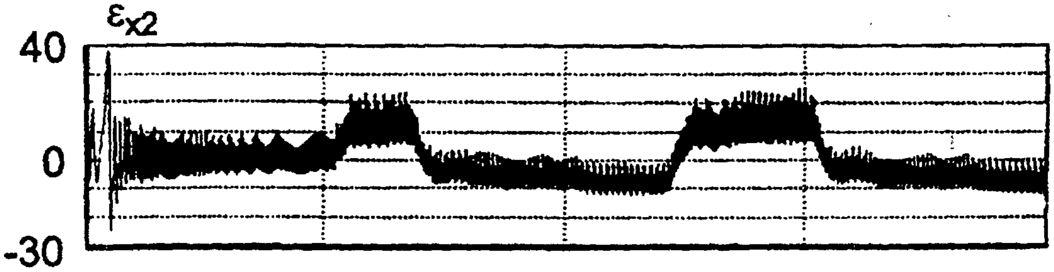

Fig 11d

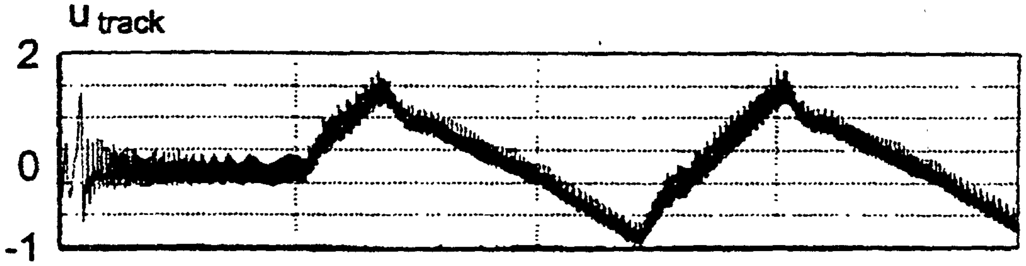

Fig 11e

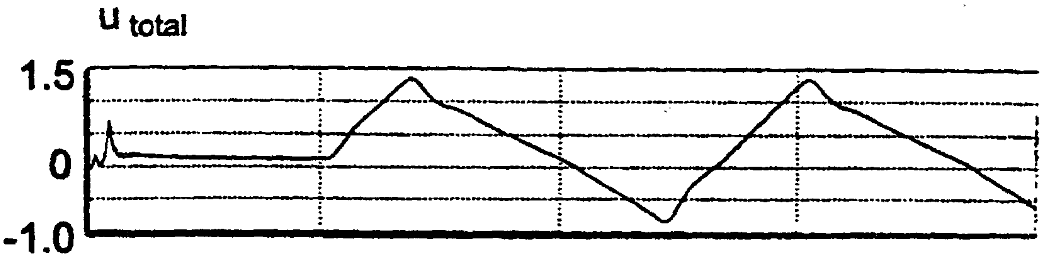

Fig 11f

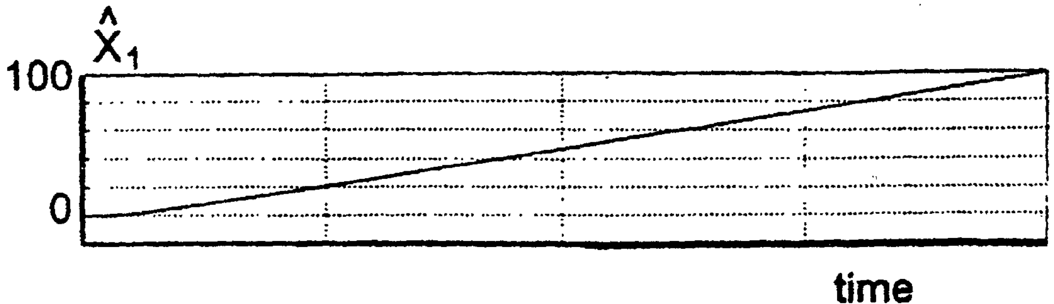

Fig 12a

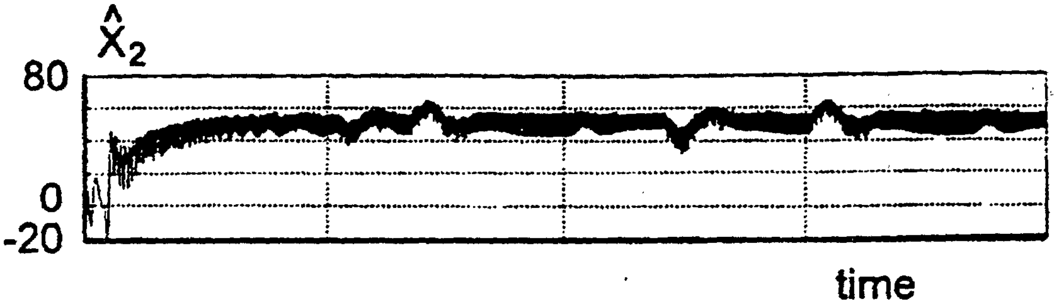

Fig 12b

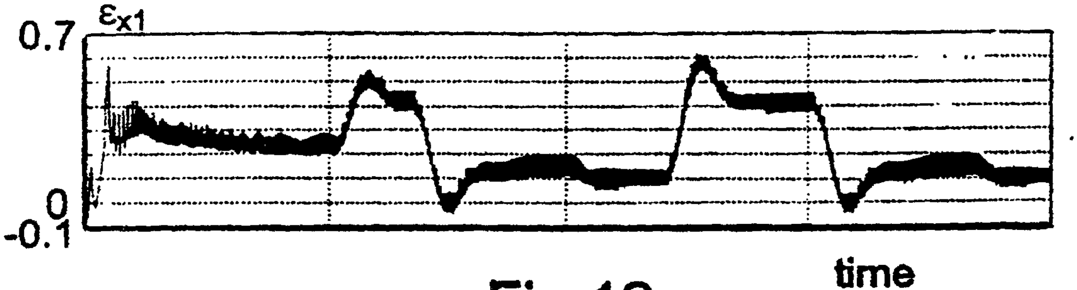

Fig 12c

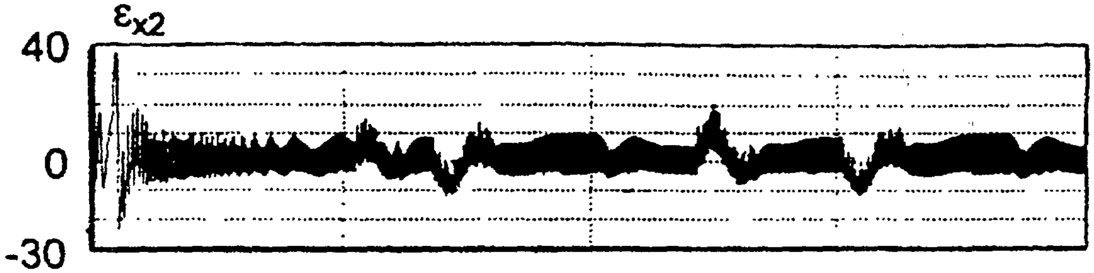

Fig 12d

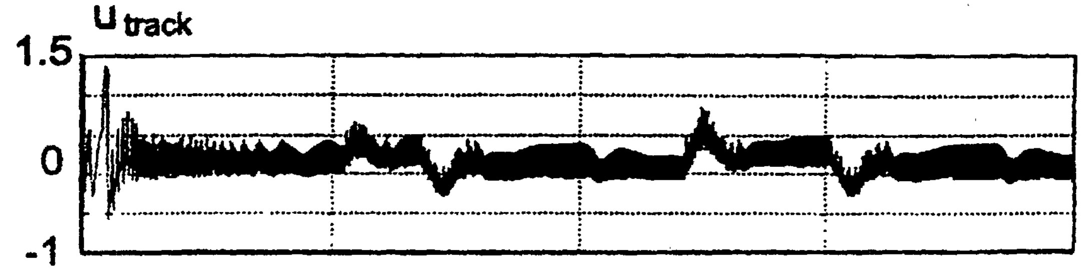

Fig 12e

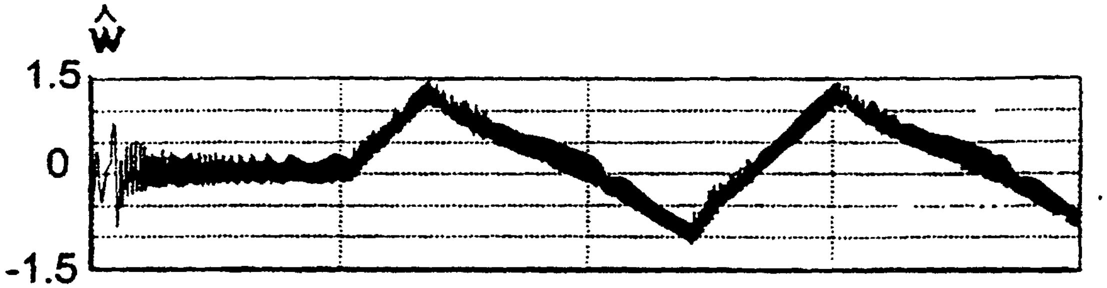

Fig 12f

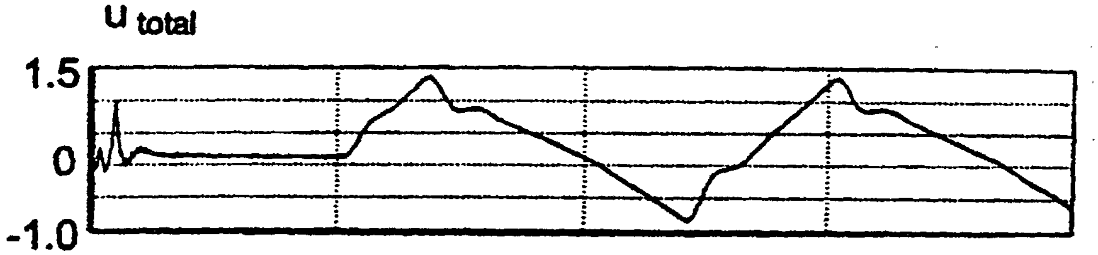

Fig 12g

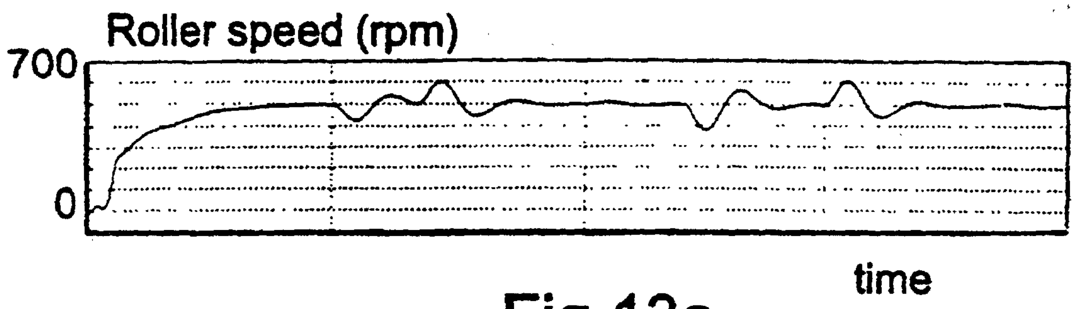

Fig 13a

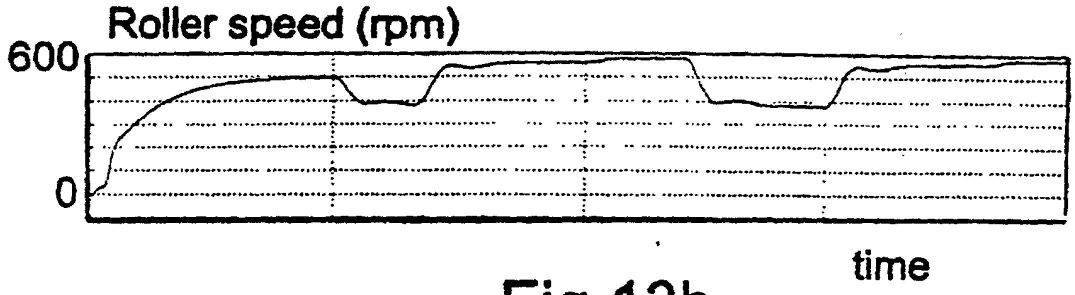

Fig 13b

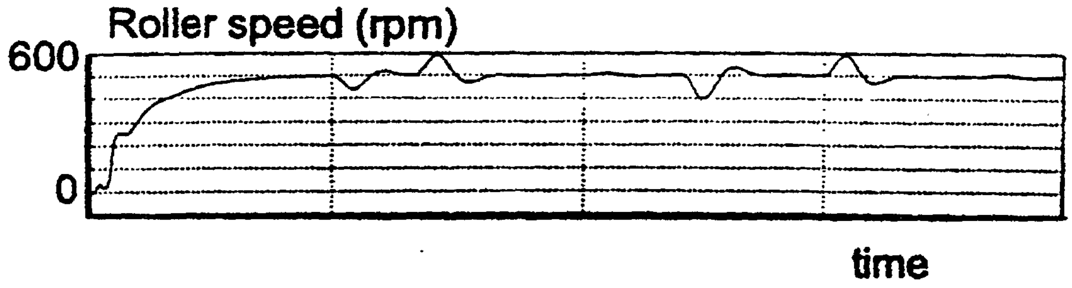

Fig 13c

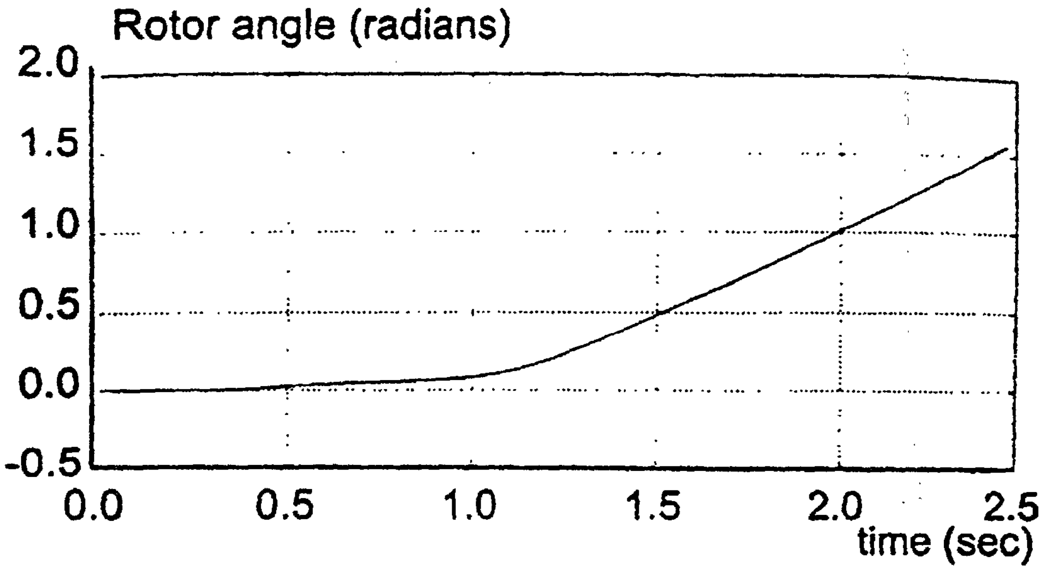

Fig 14a

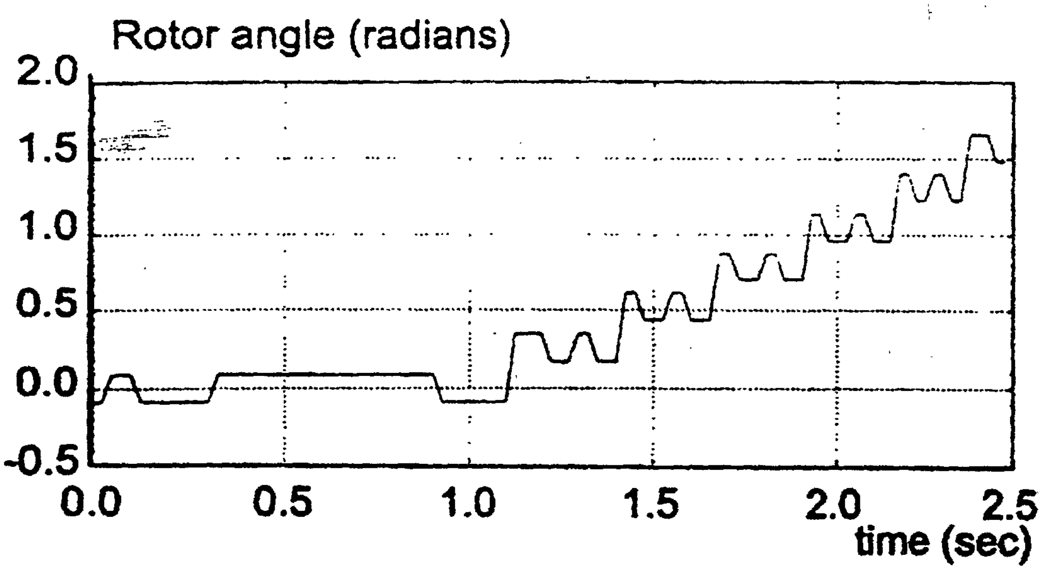

Fig 14b